$|V_{cd}|$, $|V_{cs}|$ and $f_{D_{(s)}}$ from (semi) leptonic $D_{(s)}$-decays : signals of New Physics ?

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We confront the recent improved measurements of the $D_{(s)}$ (semi) leptonic decays with Lattice QCD (LQCD) with $n_f = 3$ flavours and QCD spectral sum rules (QSSR) predictions. $D \to \mu\nu_\mu$ leptonic width data compared with theoretical determinations of f_D, leads to the value of the CKM mixing angle : $|V_{cd}| = 0.230\ (10)_{\rm exp}\ (9)_{\rm th}$. Measured ratio of the D semi-leptonic widths combined with LQCD and QSSR predictions leads to the average $|V_{cd}|/|V_{cs}| = 0.2175(88)$, and then to $|V_{cs}| = 1.068(47)$. We consider the previous determinations as improvements of the existing estimates. Using the average data of the $D_s \to \mu\nu_\mu$ (resp. $D_s \to \tau\nu_\tau$) branching ratios, one obtains : $|V_{cs}|f^{\mu}_{D_s} = (259 \pm 12)$ MeV (resp) $|V_{cs}|f^{\tau}_{D_s} = (274 \pm 13)$ MeV, which can be compared with the average of the Standard Model (SM) values from LQCD and QSSR $f_{D_s} = (240 \pm 7)$ MeV. If one uses the present determination of $|V_{cs}|$, there is an agreement with the SM prediction within 1σ. If instead, we impose the unitarity constraint $|V_{cs}| \leq 1$, or assume (as frequently done) $|V_{cs}| = |V_{ud}|$, we would obtain a deviation from the SM expectations ranging from 1.5 to 3 σ, therefore, signaling some New Physics beyond the SM.

1. Introduction

Good experimental and theoretical controls of the leptonic decay constants f_P (analogue to f_π) of charmed $D_{(s)}$ and beautiful $B_{(s)}$ (pseudo)scalar mesons are of prime importance for understanding the dynamics of the heavy light quark systems (overlap of the wave-functions, heavy quark mass-behaviour,...) in QCD. Many efforts have been devoted to this study both theoretically and experimentally [2]. The leptonic partial width of the D_q^+ is normalized as:

$$\Gamma(D_q^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi}|V_{cq}|^2 f_{D_q}^2 m_l^2 M_{D_q}\left(1 - \frac{m_l^2}{M_{D_q}^2}\right)^2 \quad (1)$$

where $q \equiv d, s$; M_{D_q} and m_l are respectively the masses of the D_q^+ meson and of the l^+ charged lepton. G_F is the Fermi constant and $|V_{cq}|$ is the CKM matrix element controlling the weak coupling of the c and q quarks. f_{D_q} is the leptonic decay constant normalized like $f_\pi = (130.4 \pm 0.2)$ MeV as:

$$(m_q + m_c)\langle 0|\bar{q}\gamma_5 c|D_q\rangle = f_{D_q} M_{D_q}^2 \ . \quad (2)$$

The previous leptonic process is helicity suppressed ($\sim m_l^2$) and the last factor in parenthesis is the familiar phase space factor. While the electron mode is tiny due to strong helicity suppression, the measurement of the τ mode involves the detection of additionnal neutrinos, such that, the muon mode is experimentally the cleanest and most accessible one. Therefore, we shall mainly consider the $D_q^+ \to \mu^+\nu_\mu$ data which (in principle) provide the most precise measurements, and show for a comparison the one from $D_s \to \tau\nu_\tau$ decay.

2. Determination of $|V_{cd}|$

For determining f_D from $D \to \mu\nu_\mu$ decay, it has become usual to assume that $|V_{cd}| = |V_{us}|$, which is an extra input in the analysis. In addition, the extraction of $|V_{us}|$ from Kl_3 is affected by the uncertainties on the value of the K-form factor, while τ-decay data give a slightly different (though consistent) value [4].

Table 1
$f_{D_{(s)}}$ and f_{D_s}/f_D from LQCD with $n_f = 3$ flavours and QSSR.

Method	f_D	f_{D_s}	f_{D_s}/f_D
LQCD[5]	201 ± 17.3	249 ± 16.3	1.24 ± 0.07
LQCD[6]	208 ± 4	241 ± 3	1.162 ± 0.009
QSSR			
Full QCD [2,3,7]	203 ± 20	235 ± 24	1.15 ± 0.04
Full QCD [8]	195 ± 20		
Analytic Cont.[9]			1.16 ± 0.03
Average	202 ± 8.3	241.7 ± 9.7	1.178 ± 0.022

The good agreeement between the measured and theoretical values of f_D [1,10,11], allows us to perform (with a good confidence) an opposite, though natural, procedure, by relying on the theoretical value of f_D for extracting more accurately $|V_{cd}|$. By combining the most recent measured $D \to \mu\nu_\mu$ branching ratio from CLEO [10,11]:

$$Br(D^+ \to \mu^+\nu_\mu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4} \ , \quad (3)$$

with the averaged value from LQCD and QSSR à la SVZ [12] given in Table 1 [3], and using the D^+ lifetime

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[2]For a recent review see e.g. [1]; For earlier reviews, see e.g. [2,3].

[3]We have only considered the ratio obtained in [9] as the decay constants obtained there are systematically lower than other predictions, which may question the systematics of the Analytic Continuation method [3], that can cancel in the ratio. We have only quoted the most recent 3-loop predictions relevant for our discussions. More complete references are given in the reviews [2,3]. We have not taken the weighted average which should be dominated by the most accurate LQCD determination where the validity of the errors are still under discussions [13]. Instead, we have taken a naïve average of the central value and have averaged the errors quadratically.

of (1040 ± 7) ps [14], we deduce:

$$|V_{cd}| = 0.230 \pm 0.010_{\rm exp} \pm 0.009_{\rm th} \ , \tag{4}$$

to be compared with :

$$|V_{us}| = 0.2165 \pm 0.0026_{\rm exp} \pm 0.0005_{\rm th} \tag{5}$$

from τ-decay [4].

3. Determination of $|V_{cs}|$

Semileptonic decays of the light K and heavy B mesons have given most of the CKM mixing parameters. In the case of the process $D^0 \to P_q^- l^+ \nu_l$, ($P_d^- \equiv \pi^-$ and $P_s \equiv K^-$) and ($l \equiv e,\ \mu$), where one can neglect the ratio $(m_l/m_c)^2$, the differential rate can be expressed as:

$$\frac{d\Gamma}{dq^2}\Big|_{D^0 \to P_q^- l^+ \nu_l} = \frac{G_F^2}{24\pi^3} p_q^3 |V_{cq}|^2 |f_+^{D\to P}(q^2)|^2 \ , \tag{6}$$

where q^2 is the invariant mass squared of the $l\nu$ system; $f_+^{D\to P}(q^2)$ is the form factor and p_q is the momentum of the light meson. CLEO data lead to the result [15]:

$$\frac{|f_+^{D\to\pi}(0)||V_{cd}|}{|f_+^{D\to K}(0)||V_{cs}|} = 0.188\ (8)\ (2)\ , \tag{7}$$

where the errors are respectively statistical and systematical. In order to use this data, we update the value of the ratio of form factors from QSSR [16] by using the recent value $\bar{m}_s(2\text{ GeV}) = (96.3 \pm 17.5)$ MeV [17] instead of the one $m_s(2\text{ GeV}) = 115.7$ MeV used in the original paper. We have also used the value of m_c in [2,3] [4]. Then, we obtain:

$$r_D \equiv |f_+^{D\to K}(0)|/|f_+^{D\to\pi}(0)| = 1.11 \pm 0.07\ , \tag{8}$$

which has almost the same value as the previous one. The error has been multiplied by $\sqrt{2}$ in order to take into account unknown higher order terms in the QCD series.

Table 2
Theoretical predictions of form factors.

Methods	$r_D \equiv \lvert f_+^{D\to K}(0)\rvert/\lvert f_+^{D\to\pi}(0)\rvert$
LQCD [5]	$1.149 \pm 0.040 \pm 0.119$
LCSR[18]	1.19 ± 0.06
QSSR[16] (updated)	1.11 ± 0.07
Average	1.155 ± 0.043

which we compare in Table 2 with some other determinations, from which we deduce the average:

$$r_D \equiv |f_+^{D\to K}(0)|/|f_+^{D\to\pi}(0)| = 1.155 \pm 0.043\ . \tag{9}$$

Some remarks are in order here:

• The determinations of the ratio compared to the absolute values are always more accurate in the QSSR calculations due to the cancellations of different systematics. The sensitivity to the higher state contributions (continuum threshold-dependence), to PT radiative corrections (which tend to cancel in the ratio), to the exact value of the charm quark mass (absent to leading order) ,... are less pronounced in the direct evaluation of the ratio than in each individual form factor. The dependence on the sum rule variable of the prediction is also weaker as shown in the figure of [16].

• This value does not come from a numerical fit but from a semi-analytic expression where all different sources of corrections can be easily controlled.

• The sum rule used here has successfully predicted (though with a modest accuracy) the absolute value of the form factor $f_+^{B\to\pi}(0) = (0.23 \pm 0.02)$ for $B \to \pi\mu\nu_\mu$ and of other semileptonic decays [19] and the decay rate $B \to K^*\gamma$ [20].

• As a good illustration of this property, the LQCD recent most precise prediction of the ratio [6]:

$$f_{D_s}/f_D = 1.162 \pm 0.009\ , \tag{10}$$

agrees within a digit with the central value from QSSR prediction obtained one decade earlier [7,2,3] [5]:

$$f_{D_s}/f_D = 1.15 \pm 0.04\ , \tag{11}$$

which is a strong indication on the reliability of the QSSR approach despite its modest accuracy [6], and a compatibility of the LQCD and QSSR results as often encountered in different channels. The same remark also holds for the absolute value of the decay constants.

• It is also important to notice that the previous ratio in Eq. (11) comes from a semi-analytic functional dependence, which is easy to control rather than from a numerical fit.

Using the previous inputs and taking into account previous remarks, we can deduce with a quite good accuracy :

$$\frac{|V_{cd}|}{|V_{cs}|} = 0.2171\ (95)_{\rm exp}\ (81)_{\rm th}\ . \tag{12}$$

which is compared in Table 3 with some alternative determinations [15]. Using the previous value of $|V_{cd}|$ into Eq. (12), one can deduce:

$$|V_{cs}| = 1.059\ (65)_{\rm exp}\ (58)_{\rm th}. \tag{13}$$

Considering as a final result, the (weighted) average of the three determinations in Table 3, we deduce:

$$\frac{|V_{cd}|}{|V_{cs}|} = 0.2175\ (88)\ , \qquad |V_{cs}| = 1.068\ (47)\ , \tag{14}$$

[4] There is an unfortunate misprint in [16]. Instead of 0.007 for the error in Eq. (24), one should read 0.07.

[5] An alternative estimate using the analytic continuation method leads to similar result but with a smaller error [9] as given in Table 1.

[6] As indicated in [7,2,3], the error in this ratio has been enlarged by $\sqrt{2}$ for a crude estimate of the unknown $m_s^4\alpha_s^2$ corrections, which I wish will be available in the near future. However, after inspection of the analytic expression of the spectral function this crude estimate can give an overestimate of the true error.

to be compared with the usual assumption:

$$|V_{cs}| \simeq |V_{ud}| = 0.97377 \pm 0.00027. \quad (15)$$

We consider these results as improvements of earlier results obtained in [16]. Further tests of the assumption $|V_{cs}| \simeq |V_{ud}|$ and some eventual deviations from the unitarity conditions can be reached in future improved measurements of D-decays. These eventual deviations may also reveal some New Physics beyond the SM expectations.

Table 3
$|V_{cd}|/|V_{cs}|$&$|V_{cs}|$ using CLEO data + Theoretical mehods. The 1st (resp) 2nd errors are experimental (resp) theoretical. The 3rd error in CLEO is due to $f_+^{D\to P}(0)$ from LQCD.

Method	$\|V_{cd}\|/\|V_{cs}\|$	$\|V_{cs}\|$	Comments
LQCD[6]	0.2257(209)(20)	1.070(70)(10)	
CLEO[15]	0.2138(100)(30)(110)	1.075(69)(47)(55)	LQCD
This work	0.2171(95)(81)	1.059(65)(58)	QSSR
Average	0.2175(88)	1.068(47)	

Table 4
$D_s \to \mu\nu_\mu$ branching ratios.

Exp.	$B_\mu \times 10^3$	$B_{\phi\pi}(\%)$
CLEO-c[21]	$5.94 \pm 0.66 \pm 0.31$	
BELLE[22]	$6.44 \pm 0.76 \pm 0.52$	
CLEO[23]	$6.2 \pm 0.8 \pm 1.3 \pm 1.6$	3.6 ± 0.9
BEATRICE[24]	$8.3 \pm 2.3 \pm 0.6 \pm 2.1$	3.6 ± 0.9
ALEPH[25]	$6.8 \pm 1.1 \pm 1.8$	3.6 ± 0.9
BABAR[26]	$6.74 \pm 0.83 \pm 0.26 \pm 0.66$	4.71 ± 0.46
Average (no rad. corr.)	$6.13 \pm 0.57^{+)}$	
	6.33 ± 0.47	

$^{+)}$ Exclude $\phi\pi^+$ mode normalizations.

4. The value of f_{D_s} from $D_s \to \mu\nu_\mu$

We shall use the previous value of the CKM angle $|V_{cs}|$ in Eq. (14) [7] for extracting the value of f_{D_s} from $D_s \to \mu\nu_\mu$, which has been emphasized to be the cleanest experimental mode. We shall use the average of the different data in Table 4 and the D_s lifetime of (0.500 ± 0.004) ps [14]. One can notice that the average including or excluding the $\phi\pi^+$ modes is almost the same. However, taking into account that the normalization to the $\phi\pi^+$ modes induce more systematic uncertainties [1], we shall only consider the 1st average which does not use this normalization. Radiative corrections will decrease the branching ratio by about 2%, which we shall include in the extraction of the decay constant. Then, we deduce:

$$f^\mu_{D_s} = (242.5 \pm 10.7_{\rm V_{cs}} \pm 11.5_{\rm exp}) \text{ MeV} . \quad (16)$$

[7] In the current literature, one often assumes $|V_{cs}| = |V_{ud}|$.

The uncertainty is comparable with the one from the theoretical average given in Table 1, and is larger than the one quoted in [1,11]. The main reason is that the result of [1,11] uses the assumption $|V_{cs}| = |V_{ud}|$ (see Eq. (15), where $|V_{ud}|$ has a tiny error.The central value of $f^{\rm exp}_{D_s}$ is also smaller than in [1,11] because the one of $|V_{cs}|$ obtained in Eq. (14) is larger than that of $|V_{ud}|$. If instead, we only impose the unitarity constraint $|V_{cs}| \leq 1$, one can deduce the lower bound:

$$|V_{cs}| \leq 1 \Longrightarrow f^\mu_{D_s} \geq (259 \pm 12) \text{ MeV} \quad (90\% \text{ CL}) . (17)$$

The usual assumption $|V_{cs}| = |V_{ud}|$ used in [1,11] would imply:

$$|V_{cs}| = |V_{ud}| \Longrightarrow f^\mu_{D_s} = (266 \pm 12) \text{ MeV} . \quad (18)$$

5. The value of f_{D_s} from $D_s \to \tau\nu_\tau$

Though expected to be less accurately measured than the $D_s \to \mu\nu_\mu$ decay, it is informative to repeat the previous analysis for the $D_s \to \tau\nu_\tau$ data, which are given in Table 5.

Table 5
$D_s \to \tau\nu_\tau$ branching ratios.

Exp.	$B_\tau \times 10^2$
CLEO-c[21]	$8.0 \pm 1.3 \pm 0.4$
CLEO-c[27]	$6.17 \pm 0.71 \pm 0.36$
ALEPH[25]	$5.8 \pm 0.8 \pm 1.8$
L3[28]	$7.4 \pm 2.8 \pm 1.6 \pm 1.8$
OPAL[29]	$7.0 \pm 2.1 \pm 2.0$
Average	6.57 ± 0.63

From the averaged branching ratio, one can deduce in MeV [8]:

$$\begin{aligned} f^\tau_{D_s} &= 256.6 \pm 11.3_{\rm V_{cs}} \pm 12.4_{\rm exp} \ : \ |V_{cs}| \text{ in Eq. (14)} \\ &\geq 273.5 \pm 13.2_{\rm exp} \ : \ |V_{cs}| \leq 1 \ \ (90\% \text{ CL}) \\ &= 280.9 \pm 13.5_{\rm exp} \ : \ |V_{cs}| = |V_{ud}| , \end{aligned} \quad (19)$$

where one can notice that the value of f_{D_s} from τ-data is about 1σ higher than the one from μ-data:

$$f^\tau_{D_s}/f^\mu_{D_s} = 1.06 \pm 0.07 . \quad (20)$$

6. Comparison with theoretical predictions

One can compare the previous experimental values with the theoretical predictions reviewed in [1,2,3], which we have selected in Table 1. From this table, the average of the direct determinations of f_{D_s} is:

$$f^{\rm dir}_{D_s} = (241.7 \pm 9.7) \text{ MeV} , \quad (21)$$

while the one obtained from the average value of f_D multiplied by the ratio f_{D_s}/f_D is:

$$f^{\rm ratio}_{D_s} = (238.0 \pm 11.8) \text{ MeV} , \quad (22)$$

[8] As mentioned in [1], the τ rate does not need to be radiatively corrected.

from which we deduce the naïve average :

$$f_{D_s}^{\rm th} = (240 \pm 7)\ {\rm MeV}\ , \tag{23}$$

where the errors have been added quadratically. We consider this result as the final theoretical result to be compared with experiments.

• *f_{D_s} from $D_s \to \mu\nu_\mu$-decay:* one can notice that the value of f_{D_s} obtained in Eq. (16) by using the value of $|V_{cs}|$ in Eq. (14) agrees quite well with the previous average of the SM predictions in Eq. (23). Discrepancies between the experimental and theoretical numbers start to be visible ($\geq 1.5\ \sigma$) when using the unitarity constraint for $|V_{cs}| \leq 1$ [see Eq. (17)] and becomes $2\ \sigma$ when one uses the additional assumption $|V_{cs}| = |V_{ud}|$ [see Eq. (18)] .

• *f_{D_s} from $D_s \to \tau\nu_\tau$-decay:* here, a comparison of the theoretical prediction shows larger discrepancies ranging from $1\ \sigma$ in the case of $|V_{cs}|$ from Eq. (14) to $3\ \sigma$ in the case $|V_{cs}| = |V_{ud}|$.

7. Interpretations: signals of New Physics ?

• Some deviations from the SM expectations can be manifest if the $|V_{cs}|$ satisfies the unitarity constraints. Therefore, more precise determinations of $|V_{cs}|$ and to a lesser extent of $|V_{cd}|$ are required for a sharp test of the SM predictions. Some eventual deviations of these CKM matrix elements from unitarity constraints can also signal some departures from the SM expectations independently of the f_{D_s} values.

• We have shown that the deviation of f_{D_s} [Eqs. (16) to (19)] from the SM expectations [Eq.(23) can be indeed quite large (3σ in the τ channel) but a sharp conclusion needs a better control of the CKM mixing matrix $|V_{cs}|$.

• We have also found in Eq. (20) that the value of f_{D_s} from $D_s \to \tau\nu_\tau$ decay can be larger than the one from $D_s \to \mu\nu_\mu$ decay. More precise measurements of f_{D_s} in both channels can then provide an universality test of the $W\mu\nu_\mu$ and $W\tau\nu_\tau$ vertices for these processes. At present, τ decay data show a slight violation [4]:

$$B_{W\to\tau\nu_\tau}/B_{W\to\mu\nu_\mu} = 1.039 \pm 0.013\ , \tag{24}$$

which can permit some new interactions (not necessary the same) at these vertices.

• Using the fact that the value of the decay constant f_{D_s} deviates from the SM predictions, some attempts to explain this deviation as due to non-standard effective interactions or/and to new scalar particles or/and to leptoquarks have been discussed in the literature [30]. Analysis of different models beyond the SM are beyond the scope of this paper though planned to be done in a future work.

8. Conclusions

We have re-examined the consequences of the recent data on (semi)leptonic $D_{(s)}$ decays by confronting them with the LQCD and QSSR theoretical calculations.

• First, these data have been used to estimate the CKM mixing angles $|V_{cd}|$ and $|V_{cs}|$. The results are given in Eq. (4) and in Eqs. (12) to (14).

• The resulting value of $|V_{cs}|$ have been used together with the $D_s \to \mu\nu_\mu$ and $D_s \to \tau\nu_\tau$ data for extracting the leptonic decay constant f_{D_s}, which behaves like $1/|V_{cs}|$ [Eqs. (16) to (19)].

• Comparing the experimental value of f_{D_s} with the theoretical averaged LQCD and QSSR determinations in Eq. (23), we conclude that a sharp detection of an eventual deviation of the SM predictions from these processes, needs either better determinations of the CKM mixing angles $|V_{cd}|$ and $|V_{cs}|$ than the one obtained in this paper, or a strict validity of the frequently used assumption $|V_{cs}| = |V_{ud}|$ or of the unitarity condition $|V_{cs}| \leq 1$. In these cases, the data indicate deviations from the SM expectations from 1.5 to $3\ \sigma$, therefore, signaling some New Physics beyond the SM.

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